

HIGH MAGNETIC FIELD MEASUREMENTS ON $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$ AND $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$

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We have measured the magnetoresistivity of the high- T_c superconductors $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$ and $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ in d.c. magnetic fields up to 25 tesla. Conservative extrapolations yield values for the upper critical field at $T=0$ of 38 ± 5 T for $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$, and of 200 ± 25 T for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$. The slope $(-dB_{c2}/dT)$ near T_c for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ is about twice as large as in $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$. This suggests that the higher T_c of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ compared with $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$ may be due to an increased density of states at the Fermi level. For both compounds the magnetoresistivity indicates a large anisotropy of the critical field and a strong spin-orbit scattering.

1. Introduction

As shown by several research groups, it is clear that the high- T_c materials are also characterized by unprecedented high values for the upper critical field [1–4]. Measurements on single crystals indicate a strong anisotropy of the upper critical field, parallel and perpendicular to the Cu-O planes with $B_{c2\parallel}/B_{c2\perp} \approx 5$ –10 [4,5].

In this paper, we analyse the critical field data of $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$ and $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, measured in static magnetic fields up to 25 T.

2. $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$

The resistive transition has been measured in a variable temperature cryostat, using standard four-probe techniques, and keeping the current density below $5 \times 10^{-3} \text{ Acm}^{-2}$. The fields were provided by a 25 tesla hybrid magnet system.

In Fig. 1 we have plotted the midpoint critical field (the field at which the resistance has 50% of the normal state resistance R_N , extrapolated from just above T_c) for $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$ as a function of temperature. Apart from a curvature near T_c , the upper critical field varies linearly with the applied magnetic field. The slope $(-dB_{c2}/dT)$ of the linear part is $\approx 1.9 \text{ T/K}$. For a comparison with the Werthamer, Helfand and Hohenberg (WHH) theory [6] for three-dimensional type-II dirty superconductors, we have calculated the upper critical field as a function of temperature and for different values of the spin-orbit coupling parameter λ_{so} . Our measurements up to 25 tesla show no deviation from linear behaviour, indicating that $\lambda_{so} \geq 5$. Evaluating the spin-orbit scattering time τ_{so} given by $\tau_{so} = 2\hbar/3\pi k_B T_c \lambda_{so}$, we find $\tau_{so} \approx 10^{-14} \text{ s}$. If we assume a Fermi velocity

$v_F \approx 10^7 \text{ cm/s}$ [7], then the spin-orbit scattering length is of the order of the lattice periodicity along the c -direction. An estimate of the midpoint critical field at $T=0$ yields $38 \pm 5 \text{ T}$ for $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$.

The Sommerfeld parameter γ can be estimated from $\gamma = 2.2 \times 10^{-4} \rho_N^{-1} (-dB_{c2}/dT)$. Assuming a normal-state resistivity $\rho_N \approx 400 \mu\Omega\text{cm}$ [7], we obtain $\gamma \approx 6 \text{ mJ(moleCu)}^{-1}\text{K}^{-2}$. This is in good agreement with the results of Batlogg *et al.* [8].

The slopes $(-dB_{c2}/dT)$ determined at the $(0.3)R_N$ - and $(0.7)R_N$ -points of the resistive transition are $\approx 1.6 \text{ T/K}$ and $\approx 2.0 \text{ T/K}$ respectively.

3. $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$

Also in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, we have observed a relatively strong effect of small applied magnetic fields. For fields above 5 T the upper critical field shifts linearly with temperature. As for La-Sr-Cu-O we find no deviation from linearity up to 25 tesla. The slope $(-dB_{c2}/dT)$ determined from the midpoint of the resistive transition, is $\approx 4.2 \text{ T/K}$. If we assume that the spin-orbit coupling is basically the same as for $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$, and that λ_{so} scales with T_c^{-1} , one would expect $\lambda_{so} \approx 2$ and a midpoint B_{c2} at zero temperature of $200 \pm 25 \text{ T}$ [3].

From $(-dB_{c2}/dT)$ we estimate that in this case $\gamma \approx 16 \text{ mJ(moleCu)}^{-1}\text{K}^{-2}$. Also for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ there is a large difference in slope $(-dB_{c2}/dT)$ when determined at different values of R/R_N , and $(-dB_{c2}/dT) \approx 3.8 \text{ T/K}$ and $\approx 4.6 \text{ T/K}$ for $(0.4)R_N$ and $(0.6)R_N$ respectively. The broadening can again be attributed to a strong anisotropy of the upper critical field.

4. Anisotropy

We have attributed the variation of $(-dB_{c2}/dT)$ at different values of R/R_N to anisotropy of the upper critical

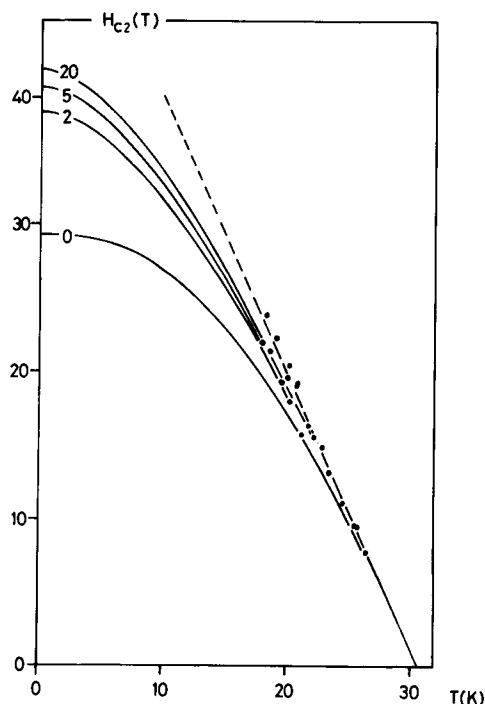


Figure 1. Upper critical field of $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$, compared with a calculation according to the Werthamer, Helfand and Hohenberg theory, for different values of the spin-orbit coupling parameter λ_{so} (see text).

field [3]. A similar analysis has subsequently been made by Welch *et al.* [9]. We assume that the critical field $B_{c2}(\Theta)$ of a crystallite depends on its orientation and is given by the Tinkham formula for thin superconducting films [10]. Furthermore, as the conduction is a percolation problem, we take the phenomenological equation for electrical conductivity of microscopically inhomogeneous materials proposed by Davidson and Tinkham [11]. The anisotropy ratio $\alpha = B_{c2}/B_{c2\perp}$ is fitted to obtain a consistent description of the slopes $(-dB_{c2}/dT)$ obtained at all values of R/R_N . For $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$ we find an anisotropy ratio $\alpha = 9 \pm 2$, and for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, $\alpha = 15 \pm 5$.

In a similar analysis of their data of the resistive transition, Welch *et al.* found an anisotropy ratio of 25 - 50 for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ [9]. In their case however, a broadened resistive transition due to possible inhomogeneities may have lead to an overestimate of the anisotropy. In our case, we restricted ourselves to the analysis of the slopes $(-dB_{c2}/dT)$ at fields above 5 T, and the effect of inhomogeneities does not play a role.

Also, one should realize that in the model of Davidson and Tinkham one assumes that all crystallites are in metallic contact. In other words, one assumes that

the first superconductive percolation path is formed if the fraction of superconducting crystallites is 1/6. From tunneling measurements it is clear that in many cases the grains are covered with an insulating oxide layer. This will lead to an increase of the percolation limit, and consequently to a lower value of the inferred anisotropy ratio. If we assume that the first percolative superconducting path is formed when 25% of the crystallites is superconducting, the same analysis as above yields an anisotropy ratio $\alpha \approx 6$ for $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$ and $\alpha \approx 10$ for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$.

5. Conclusions

The upper-critical-field data for polycrystalline material suggest a large anisotropy $B_{c2}/B_{c2\perp} \approx 6$ for $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$, and of ≈ 10 for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$. The Sommerfeld parameter γ for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ is approximately twice as large as for $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$. This indicates that the higher T_c of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ may be due to a larger density of states at the Fermi level. A comparison with the WHH theory of type-II superconductors yields an estimate for the midpoint upper critical field $B_{c2} = 38 \pm 5$ T for $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}$, and $B_{c2} = 200 \pm 25$ T for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$.

We gratefully acknowledge the technical support of C.J. Beers, K. van Hulst, H. van Luong, and J. Rook. This work was part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie (FOM)

References:

- [1] T.P. Orlando, K.A. Delin, S. Foner, E.J. McNiff, Jr., J.M. Tarascon, L.H. Greene, W.R. McKinnon, and G.W. Hull, *Phys. Rev. B*, **35**, 5347 (1987).
- [2] T.P. Orlando, K.A. Delin, S. Foner, E.J. McNiff, Jr., J.M. Tarascon, L.H. Greene, W.R. McKinnon, and G.W. Hull, *Phys. Rev. B* **35**, 7249 (1987).
- [3] P.J.M. van Bentum, H. van Kempen, L.E.C. van de Leemput, J.A.A.J. Perenboom, L.W.M. Schreurs, and P.A.A. Teunissen, *Phys. Rev. B* **36**, 5279 (1987).
- [4] H. Noel, P. Gougeon, J. Padiou, J.C. Levet, M. Potel, O. Laborde, and P. Monceau, *Solid State Comm.* **63**, 915 (1987).
- [5] T.K. Worthington, W.J. Gallagher, and T.R. Dinger, *Phys. Rev. Lett.* **59**, 1160 (1987).
- [6] N.R. Werthamer, E. Helfand, and P.C. Hohenberg, *Phys. Rev.* **147**, 295 (1966).
- [7] W.K. Kwok, G.W. Crabtree, D.G. Hinks, D.W. Capone, J.D. Jorgensen and K. Zhang, *Phys. Rev. B* **35**, 5343 (1987).
- [8] B. Batlogg, A.P. Ramirez, R.J. Cava, R.B. van Dover, and E.A. Rietman, *Phys. Rev. B* **35**, 5340 (1987).
- [9] D.O. Welch, M. Suenaga, and T. Asano, *Phys. Rev. B* **36**, 2390 (1987).
- [10] M. Tinkham, *Phys. Rev.* **129**, 2413 (1963).
- [11] A. Davidson and M. Tinkham, *Phys. Rev. B* **13**, 3261 (1976).